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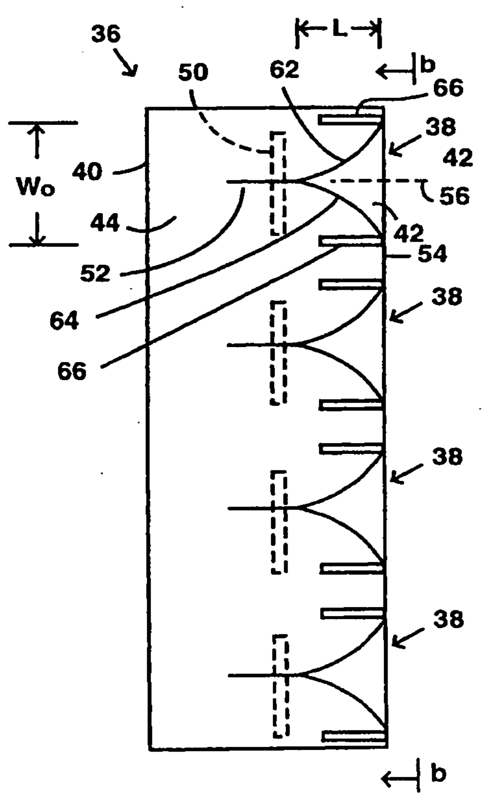
(54) Title: ARRAY ANTENNA FOR D-SHAPED, H-PLANE RADIATION PATTERN



(57) Abstract: A tapered slot array antenna (36) and methods for providing a D-shaped, H-plane radiation pattern. A plurality of tapered slot microstrip antennas are formed in an array on a conventional printed circuit board. The openings of the tapered slots (38) and the lengths of the slots are set substantially equal to one-half the wavelength of the nominal operating frequency of the array antenna (36). At least one decoupling slot (66) is disposed on each side of each tapered slot, the length of the decoupling slots being substantially equal to one-half the wavelength of the nominal operating frequency. One or more such arrays (36) may be mounted on a vehicle to obtain a uniform radiation pattern around a desired portion of the vehicle.

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ARRAY ANTENNA FOR D-SHAPED, H-PLANE RADIATION PATTERN

TECHNICAL FIELD

This invention relates to radio antennas and related methods, particularly to compact, short-wavelength antennas that provide a D - shaped, H - plane radiation pattern and are readily manufacturable.

BACKGROUND OF THE INVENTION

Usually, the goal of antenna design is to achieve high gain, high directionality and wide bandwidth. In the short-wavelength microwave and millimeter wave spectra this has led to the development of a class of antennas known as slotted microstrip antennas. These essentially comprise a dielectric substrate having a metal circuit formed thereon, the metal circuit defining a conductive ground plane and a radiation slot therein to which a radio frequency ("RF") electrical signal is coupled to produce electromagnetic radiation. The radiation slot has an open front end, typically along an edge of the substrate, and is coupled to the electrical signal at an opposite, back end. Often, the radiation slot is tapered so as to provide a wide range of wavelengths over which the antenna can operate, the low cutoff frequency being determined by the width of the opening of the radiation slot at the front end and the high cutoff frequency being determined by the width of the radiation slot at the back end. Antennas of this type are described, for example in P.J. Gibson, "The Vivaldi Aerial," Proc. 9th Microwave Conf. (Brighton, UK), 1979, pp. 101- 105; K. Yngvesson, et al., "Endfire Tapered Slot Antennas on Dielectric Substrates," IEEE Transactions on Antennas and Propagation, Vol. AP -33, No. 12, December, 1985; U. Kotthaus et al., "Investigation of Planar Antennas for Submillimeter Receivers," IEEE Transactions on Microwave Theory and Techniques, p. 375, Vol. 37, No. 2,

February, 1989; and N. Herscovici, "Wideband Antenna Design Serves Wireless Systems," Microwaves & RF (May 1998).

Conventional slotted microstrip antennas are relatively sensitive to material and manufacturing tolerances. This is because the operating wavelength of the antenna is a function of both the width of the radiation slot and the dielectric constant of the substrate material. The width is affected both by manufacturing accuracy and the thermal coefficient of expansion of the metal which forms the conductive ground plane, and the dielectric constant of the substrate is affected by the uniformity of the substrate material, the change in dielectric constant of the substrate with changes in temperature, and the thermal coefficient of expansion of the substrate. Consequently, specialized materials have been developed for these antennas. These materials combine low coefficients of thermal expansion, a relatively uniform dielectric constant (ordinarily a relative value of less than about plus or minus 0.1 for G10 epoxy) and low variation in dielectric constant with changes in temperature. Even with such material, close fabrication tolerances must be observed to ensure that they antenna meets operational specifications.

Like other types of antennas, slotted microstrip antennas can be arranged in arrays to provide higher gain and directivity, as is commonly understood in the art. Slotted microstrip array antennas are discussed, for example, in P. Bhartia et al., Millimeter-Wave Microstrip and Printed Circuit Antennas, p. 227-30 (Artech House, Inc., 1991) and K. Yngvesson et al., "The Tapered Slot Antenna - A New Integrated Element for Millimeter - Wave Applications," IEEE Transactions on Microwave Theory and Techniques, p. 365, Vol. 37, No. 2, February, 1989. However, such arrays are only effective to produce a uniform radiation pattern if the width of the slot reaches the half-wavelength of the nominal frequency of radiation at a significant distance back from the front of the

radiation slot. Otherwise the edge currents of adjacent radiation slots will interact, which produces many side lobes in the radiation pattern and results in wasted energy or unwanted interference, or both.

A common way of coupling the RF signal to the back end of the radiation slot is by forming a feed slot at the back end of the radiation slot along the propagation axis of the radiation slot, and forming an elongate microstrip conductor on the opposite side of the substrate from the feed slot, ordinarily at right angles thereto. This type of coupling is disclosed, for example, in J. Knorr, "Slot-Line Transitions," IEEE Transactions on Microwave Theory and Techniques, p. 548, May, 1974, and in the Yngvesson and Kotthaus articles mentioned above.

Sometimes, the objective of antenna design is not necessarily high gain, high directivity and wide bandwidth. Rather, the predominate goal may be to provide a specific radiation pattern, favorable manufacturability or insensitivity to temperature changes and variations in material characteristics. For example, where a short-wavelength antenna is to be mounted on a vehicle for communication in a wide range of directions, a D - shaped radiation pattern is desirable because energy can be directed essentially entirely away from the vehicle. This would ensure that the vehicle itself does not affect the radiation pattern, while providing for maximum possible azimuthal coverage. However, this goal is counter to the usual goals of antenna design and presents different problems.

It is commonly understood in the art that an array of spaced dipoles can be used to produce a D - shaped radiation pattern. However, it is mechanically cumbersome to manufacture and mount such an array, for example on a vehicle. This is, in part, because of the need to provide a large number of dipoles, to feed each dipole with a separate coaxial connection, and to provide adequate

mechanical support for all of the dipoles so as to maintain radiation pattern stability.

Accordingly, there has been a need for an improved approach to the design, manufacture and use of slotted microstrip antennas for short microwave and millimeter wave RF signals to serve a wider range of objectives.

SUMMARY OF THE INVENTION

The present invention meets the aforementioned need by providing a slotted microstrip array antenna for producing a D - shaped, H - plane radiation pattern wherein each radiation slot preferably has a maximum width, at the front thereof, substantially equal to one-half the wavelength of the nominal operating frequency and is separated from the next adjacent radiation slot by a decoupling slot so that edge currents from adjacent slots do not interfere with one another. Preferably, a decoupling slot is disposed on both sides of each radiation slot so as to fix the maximum effective radiation opening and produce the D - shaped, H - plane radiation pattern. Preferably, the length of the radiation slot and the length of the decoupling slots are substantially equal to one-half the wavelength of the nominal operating frequency. Also preferably, the radiation slots are tapered with edges that are substantially exponential in shape.

A microstrip conductor is disposed on the opposite side of the antenna substrate from each radiation slot substantially perpendicular to the radiation axis of the radiation slot so as to couple RF energy to the radiation slot. Preferably, a coupling slot is disposed at the back of the radiation slot collinear with the propagation axis of the radiation slot so as to receive energy from the conductor.

Due to the dimensions of the radiation slots relative to the nominal operating frequency and signal bandwidth, the antenna is relatively insensitive to manufacturing and material variations. Consequently, the antenna may be

fabricated economically and efficiently from standard printed circuit board material and using standard printed circuit board fabrication techniques.

A plurality of the array antennas may be mounted on a vehicle so as to be substantially identically polarized, with their principal directions of radiation pointed away from a the vehicle and oriented so as to produce maximum uniform azimuthal coverage for the vehicle.

Accordingly, it is a principal object of the present invention to provide a novel and improved array antenna and fabrication method for producing a slotted microstrip radiator having a D - shaped, H - plane radiation pattern.

It is another principal object of the invention to provide novel and improved method for minimizing the radiation pattern sensitivity of a slotted microstrip antenna to manufacturing and material variations.

It is yet a further principal object of the present invention to provide a novel and improved method for optimizing the radiation pattern of a short wavelength radio communications system mounted on a vehicle

The foregoing and other objects, features, and advantages of the invention will be more readily understood upon consideration of the following detailed description of the invention, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1(a) is a plan view of the front side of a prior art slotted microstrip antenna known as a Vivaldi antenna.

Figure 1(b) is a plan view of the back side of the antenna of Figure 1(a).

Figure 2 is an exemplary plot of an E - plane radiation pattern for a prior art Vivaldi antenna as shown in Figures 1(a) and 1(b).

Figure 3(a) is an exemplary plot of an H - plane radiation pattern for a prior art array antenna employing

slotted microstrip antennas of the type shown in Figures 1(a) and 1(b).

Figure 3(b) is an exemplary plot of an E - plane radiation pattern for a prior art array antenna employing slotted microstrip antennas of the type shown in Figures 1(a) and 1(b).

Figure 4(a) is a plan view of the front side of a preferred embodiment of a tapered slot microstrip array antenna according to the present invention.

Figure 4(b) is an edge view of the array antenna of Figure 4(a), taken along line b - b thereof.

Figure 4(c) is a plan view of the back side of the antenna of Figure 4(a).

Figure 5(a) is an exemplary plot of an E - plane radiation pattern for the array antenna of Figures 4(a) - 4(c).

Figure 5(b) is an exemplary plot of an H - plane radiation pattern for the array antenna of Figures 4(a) - 4(c).

Figure 6(a) is a side view of a haul truck with a pair of array antennas according to the present invention mounted thereon.

Figure 6(b) is a top view of the haul truck of figure 6(a), showing the radiation pattern of the pair array antenna.

BEST MODE FOR CARRYING OUT THE INVENTION

An exemplary prior art slotted microstrip antenna 10 is shown in Figures 1(a) and 1(b). This antenna comprises a substantially planar dielectric substrate 12, having a front surface 14, shown in Figure 1(a), and a back surface 16, shown in Figure 1(b). A conductive ground plane 18 is disposed on the front surface 14 and a radiation slot 20 is formed in the conductive ground plane. The front of the radiation slot 20 is disposed along a front edge 22 of the substrate 12, and the back of the radiation slot terminates at a coupling stub 24 which is collinear with the radiation

axis 26 of the radiation slot. A stripline conductor 28 is disposed on the back surface of the substrate with its elongate dimension oriented perpendicular to the elongate dimension of the coupling stub 24, for coupling energy to the stub and, thus, to the radiation slot 20. The microstrip conductor is typically fed by a coaxial conductor 30.

The antenna shown in Figures 1(a) and 1(b) is referred to as a tapered slot antenna because the width W of the radiation slot increases along the radiation axis 26 from the back of the radiation slot to the front thereof, the maximum width at the front being designated herein as Wo. The length of the radiation slot from back to front is designated herein as L. More specifically, the radiation slot of the exemplary prior art slotted microstrip antenna of Figures 1(a) and 1(b) has a first edge 32 and a mirror-image second edge 34 which vary exponentially with distance along the radiation axis 26 from the back of the radiation slot to the front thereof. This is called a "Vivaldi" antenna and is commonly known in the art. A representative radiation pattern for a Vivaldi antenna is shown in Figure 2, the E - field plane (parallel to the plane of the substrate) and H - field plane (perpendicular to the plane of the substrate) patterns being essentially identical.

Depending on the radiation bandwidth and radiation pattern desired, slotted microstrip antennas have been made with no taper, linear taper, stepped taper or exponential taper. While the taper increases the bandwidth, since the frequency of radiation is that having a half wavelength equal to the width W of the slot at any given position along the radiation axis, it also produces a broad radiation pattern. On the other hand, linear taper and zero taper slots produce more and more side lobes, respectively, in the radiation pattern.

Slotted microstrip antennas have been arranged in arrays, both side-by-side and stacked parallel to one another. The salient advantage of such arrays is that they

combine broad bandwidth with high gain in both the E-field and H-field planes. However, arrays operating at a half wavelength near the width of the front openings of the radiation slots tend to produce undesirable side lobes, as shown in Figures 3(a) and 3(b).

Although the antenna array of the present invention employs tapered slots, it is fundamentally different from the prior art in least the following salient respects. First, the taper is provided to reduce sensitivity to manufacturing and material variations rather than to achieve wideband radiation; indeed, the array antenna is most suited for relatively narrow-band communication. Second, the architecture significantly reduces side lobes. Third, the architecture provides a relatively broad, uniform, D - shaped radiation pattern in the H - plane and a relatively narrow E - plane pattern, rather than an essentially symmetrical pattern for both field planes.

Turning now to Figures 4(a), 4(b) and 4(c), the preferred embodiment of the present invention comprises an array antenna 36 comprising a plurality of substantially-identical tapered radiation slots 38 arranged side-by-side on a single, substantially- flat dielectric substrate 40. The substrate has a front surface 42, shown in Figure 4(a), a conductive ground plane 44 disposed on the front surface in which the radiation slots 38 are formed, a back surface 46, shown in Figure 4(c), and a coupling microstrip conductor 50 disposed on the back surface for each radiation slot for coupling RF energy thereto. Each radiation slot has a coupling stub 52 disposed at the back end thereof for receiving RF energy from a coupling microstrip. Figure 4(b) shows a front view of the front edge 54 of the antenna array.

The coupling microstrip conductor 50 for each radiation slot 38 is disposed so that its elongate axis is perpendicular to the elongate radiation axis 56 of its corresponding coupling stub and radiation slot. In this array, a branching microstrip conductor 58, fed by a single

RF transmission line, such as coaxial conductor 60, is used to feed all of the coupling microstrip conductors 52 and, thus, the radiation slots 38. While the preferred embodiment of the invention employs the foregoing signal feed and coupling arrangement in combination with features described below, it is to be recognized that other feed arrangements may be employed without departing from the most fundamental principles of the invention.

To produce a broad H - plane radiation pattern, the maximum width Wo and the length L of each radiation slot is preferably made substantially equal to one-half the wavelength of the nominal operating frequency of the antenna. To provide for a relatively narrow bandwidth of frequencies and reduce the sensitivity of the antenna to manufacturing and temperature variations in the width of the radiation slot, the first and second mirror image edges 62 and 64 of the radiation slots are preferably exponential. Thus, for a relatively narrow bandwidth, e.g., 10 MHz, at a nominal operating frequency of, e.g., 2.4 GHz, variations in the width of the radiation slot along the radiation axis slightly change the position along that axis at which the power is radiated, but do not significantly affect the gain or radiation pattern as a function of frequency. For ease of manufacturability, in the application of the present invention the edges 62 and 64 can be approximated as arcs of a circle with no significant degradation in performance.

Ordinarily, the length of the radiation slot of a slotted a microstrip antenna would be many wavelengths long to achieve high gain. The relatively short length of the radiation slots 38 of the present invention produces relatively low gain for each radiation slot. Accordingly, a plurality of radiation slots are assembled side-by-side into an array to produce an array antenna gain in the E - plane that overcomes the reduced gain for each individual radiation slot, as shown by the radiation pattern in Figure 5(a), while providing the desired D - shaped radiation

pattern in the H - plane, as shown by the radiation pattern in Figure 5(b).

Each of the radiation slots 38 of the preferred embodiment of the invention is bracketed by a respective pair of substantially constant-width decoupling slots 66. Each decoupling slot is disposed so that its elongate axis is substantially parallel to the radiation axis 56 and has a front opening at the front edge of the substrate immediately adjacent the front opening of its corresponding radiation slot 38. In accordance with the preferred embodiment of the invention, the length of the decoupling slots is substantially about one-half the wavelength of the nominal operating frequency of the antenna.

The decoupling slots provide several advantages. First, they ensure that radiation from the opening of the radiation slot terminates at the edge of the opening, which helps confine the radiation pattern to a D - shape. Second, they ensure that current at an edge of one radiation slot near the front opening of the slot is in phase with current near the front of the next adjacent edge of the next adjacent radiation slot, so as to prevent interference between the currents of adjacent radiation slots and thereby eliminate unwanted side lobes that would otherwise be produced. Third, by isolating adjacent areas on the antenna surface, they make the array antenna less sensitive to manufacturing variations in feature dimensions and permit the antenna to be made with material that satisfies more tolerant specifications such as flatness and dielectric constant.

While in the preferred embodiment each radiation slot has a distinct pair of decoupling slots, so as to make the array antenna even less sensitive to manufacturing variations, it is to be recognized that a single decoupling slot between each radiation slot could be used without departing from the most fundamental principles of the invention.

While the foregoing relative dimensions are preferred, it is to be recognized that the radiation slot could reach a width W equal to one-half the wavelength of the nominal operating frequency at some point back from the front of the radiation slot, that is, the radiation point, without departing from the most fundamental principles of the invention.

Turning to Figures 6(a) and 6(b), a haul truck 62 of the type that is typically used in mining operations is shown with two array antennas 36 and 38 according to the present invention mounted on the front corners thereof. Although the array antenna of the present invention can be advantageously used with any vehicle, because the D - shaped, H - plane radiation pattern ensures that very little RF energy is reflected off the vehicle, a mining haul truck presents a special challenge because, to prevent their destruction, antennas can only be mounted on the cab of the truck, yet a substantially 360 degree uniform gain radiation pattern is needed to communicate in all directions. As can be seen by Figure 6(b), in particular, the array antennas ensure that very little RF energy is reflected off the haul truck and that a nearly 360 degree radiation pattern is achieved. At the same time, since the array antennas are used for terrestrial communication it is unnecessary and undesirable to radiate energy much above the horizon; the relatively narrow E - plane pattern of the array antenna of the invention confines the vertical radiation pattern to a relatively narrow angle, thereby providing high gain and avoiding wasted energy.

The terms and expressions which have been employed in the foregoing specification are used therein as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding equivalents of the features shown and described or portions thereof, it being recognized that the scope of the invention is defined and limited only the claims which follow.

CLAIMS:

1. A tapered slot array antenna for providing a substantially D -shaped, H - field plane radiation pattern, comprising:

a dielectric substrate having a front surface and a back surface;

a conductive ground plane disposed on the front surface of said dielectric substrate;

a plurality of tapered radiation slots formed in said conductive ground plane, each of said radiation slots having a wide, open end disposed at a common edge of said substrate and a narrow end; and

one or more decoupling slots, at least one said decoupling slot being disposed between each pair of radiation slots, said decoupling slots having an open end disposed at the same common edge as said radiation slots and a length selected so that, at the nominal operating wavelength of the antenna, the current at the radiation point on one edge of a given tapered slot closest to the next adjacent tapered slot is substantially in phase with the current at the radiation point on the next adjacent edge of said next adjacent radiation slot.

2. The array antenna of claim 1, wherein the open ends of said radiation slots have a width substantially equal to one-half the nominal operating wavelength of the array antenna.

3. The array antenna of claim 1, wherein the lengths of said radiation slots are substantially equal to one-half the nominal operating wavelength of the array antenna.

4. The array antenna of claim 1, wherein the lengths of said decoupling slots are substantially equal to one-half the nominal operating wavelength of the array antenna.

5. The array antenna of claim 1, further comprising one or more conductors disposed on the back side of said dielectric for coupling electromagnetic energy to said radiation slots.

6. The array antenna of claim 1, wherein the edges of said radiation slots are tapered substantially exponentially.

7. The array antenna of claim 1, mounted on a vehicle so that the principal direction of radiation of the antenna points away from the side of the vehicle.

8. A method for reducing the radiation pattern sensitivity of a slotted microstrip antenna to manufacturing and material variations, the antenna comprising a dielectric substrate having a front surface and a back surface, a conductive ground plane disposed on the front surface of said dielectric substrate, and a tapered radiation slot formed in said conductive ground plane, the radiation slot having a wide, open end disposed at a common edge of said substrate, a narrow end and edges therebetween, the method comprising:

selecting a nominal wavelength of a signal to be radiated;

setting the width of said open end of said radiation slot substantially equal to one-half said nominal wavelength;

setting the length of said radiation slot substantially equal to one-half said nominal wavelength; and

tapering said edges of the radiation slot substantially exponentially from said wide, open end to said narrow end of said radiation slot.

9. A method for constructing a slotted microstrip array antenna so as to substantially eliminate side lobes in the H-field plane thereof, comprising:

providing a dielectric substrate having a front surface and a back surface;

providing a conductive ground plane disposed on the front surface of said dielectric substrate;

providing a plurality of tapered radiation slots formed in said conductive ground plane, each of said radiation slots having a wide, open end disposed at a common edge of said substrate and a narrow end; and

providing one or more decoupling slots, at least one said decoupling slot being disposed between each pair of radiation slots, said decoupling slots having an open end disposed at the same common edge as said radiation slots and a length selected so that, at the nominal operating wavelength of the antenna, the current at the radiation point on one edge of a given tapered slot closest to the next adjacent tapered slot is substantially in phase with the current at the radiation point on the next adjacent edge of said next adjacent radiation slot.

10. A method for optimizing the radiation pattern of a short wavelength radio communications system mounted on a vehicle, comprising:

mounting on said vehicle in laterally-spaced relation to one another a plurality of radio antennas, each antenna having a substantially D-shaped, H-field plane radiation pattern; and

orienting said antennas so they are substantially identically polarized, their principal radiation directions are away from the vehicle and their relative respective radiation axes provide maximum uniform azimuthal gain.

11. The method of claim 10, wherein said antennas each comprise:

a dielectric substrate having a front surface and a back surface;

a conductive ground plane disposed on the front surface of said dielectric substrate;

a plurality of tapered radiation slots formed in said conductive ground plane, each of said radiation slots having a wide, open end disposed at a common edge of said substrate and a narrow end; and

one or more decoupling slots, at least one said decoupling slot being disposed between each pair of radiation slots, said decoupling slots having an open end disposed at the same common edge as said radiation slots and a length selected so that, at the nominal operating wavelength of the antenna, the current at the radiation point on one edge of a given tapered slot closest to the next adjacent tapered slot is substantially in phase with the current at the radiation point on the next adjacent edge of said next adjacent radiation slot.

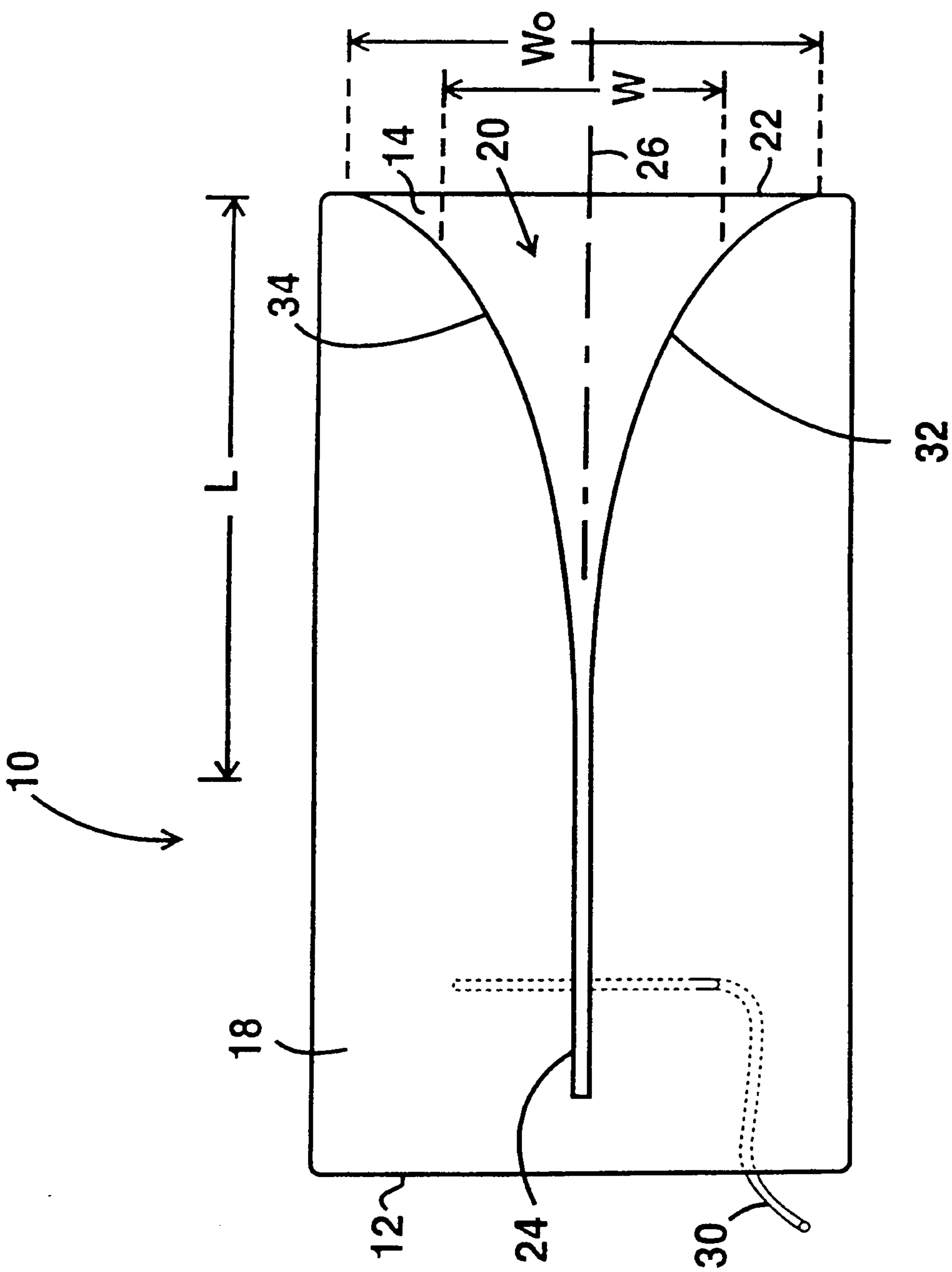

FIG. 1 (a)
(PRIOR ART)

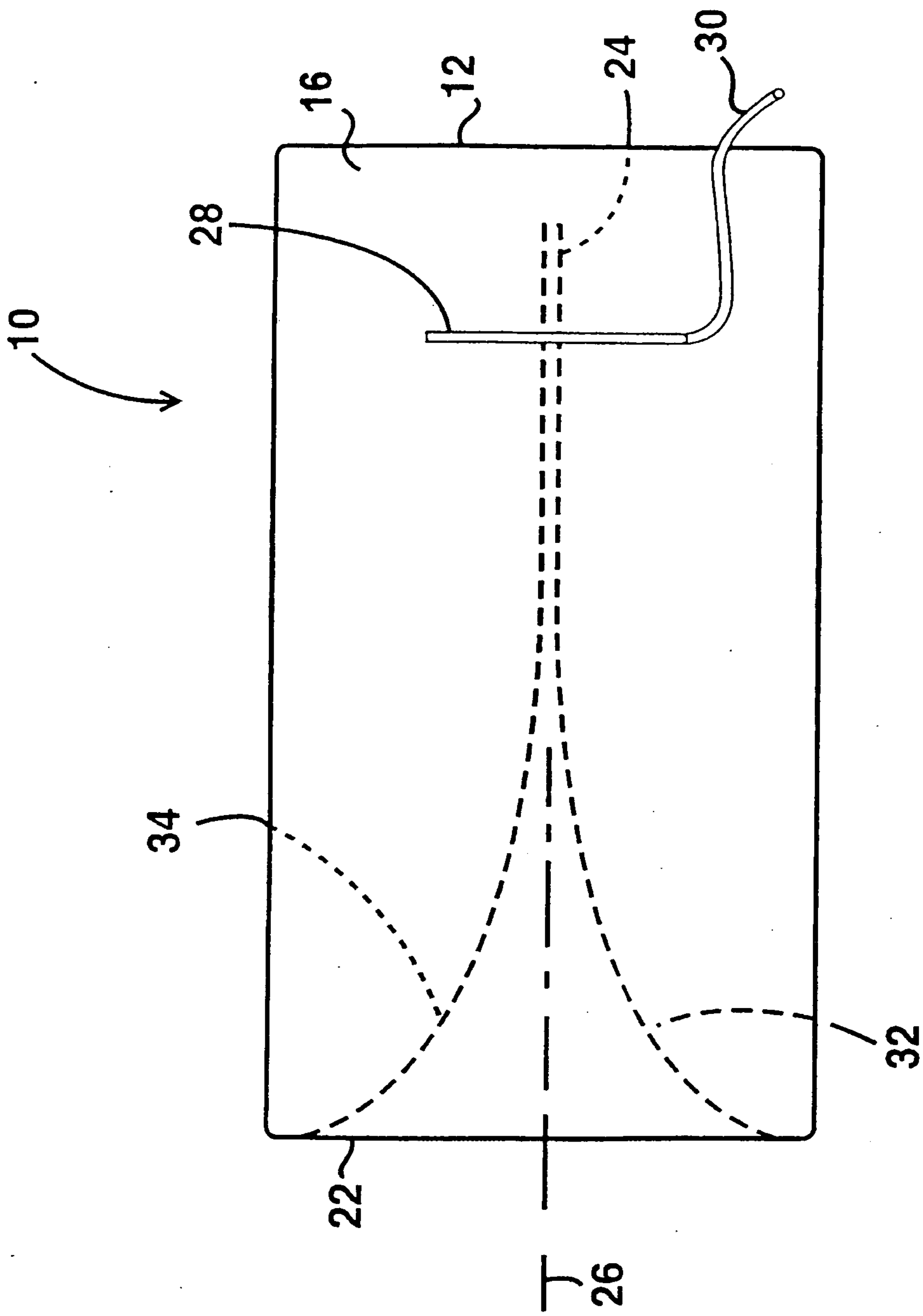

FIG. 1 (b)
(PRIOR ART)

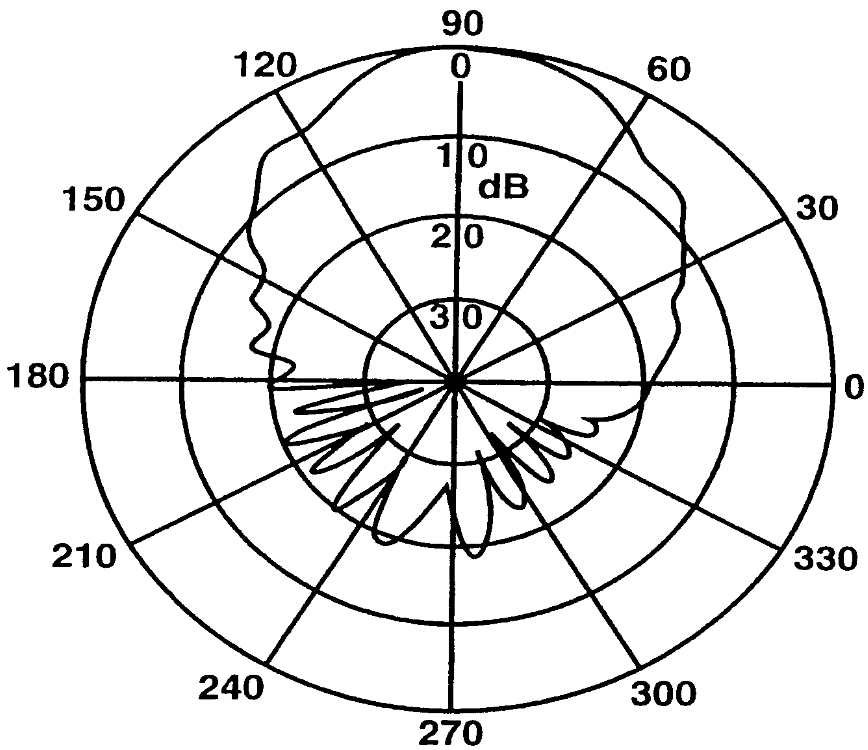

FIG. 2
(PRIOR ART)

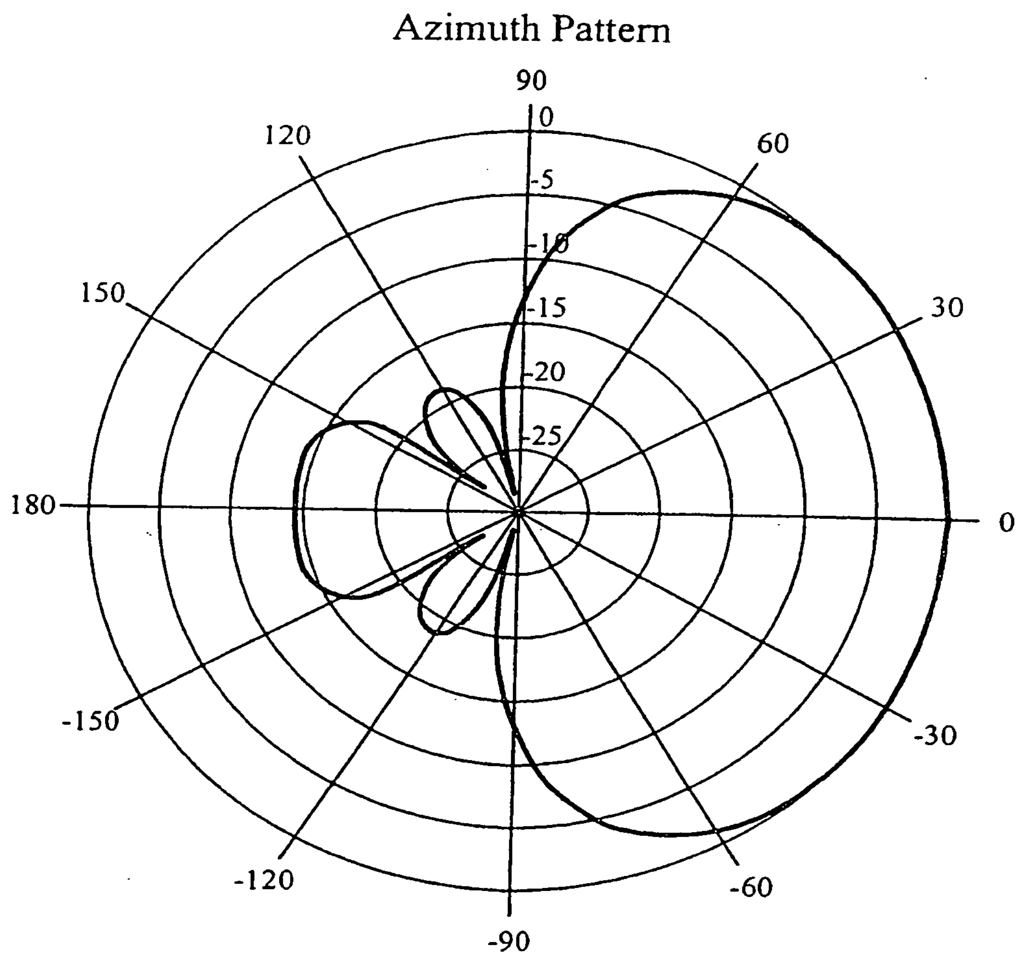

FIG. 3(a)
(PRIOR ART)

Elevation Pattern

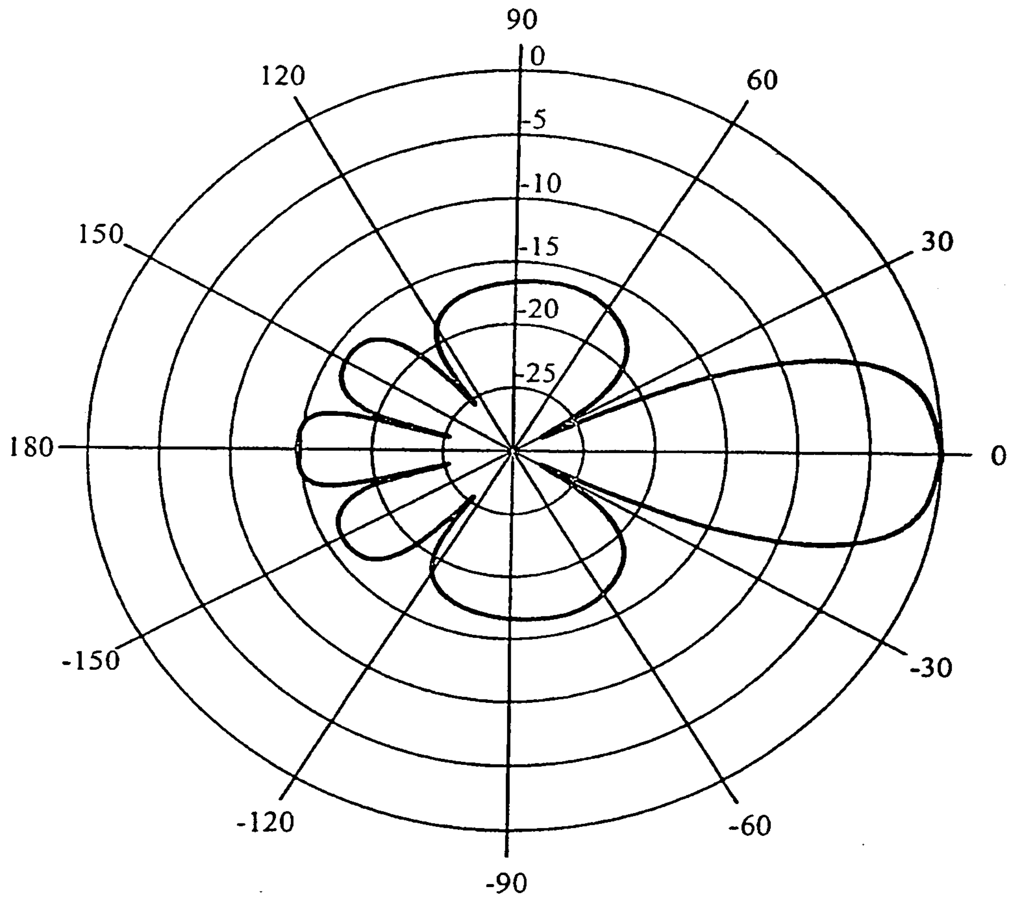

FIG. 3(b)
(PRIOR ART)

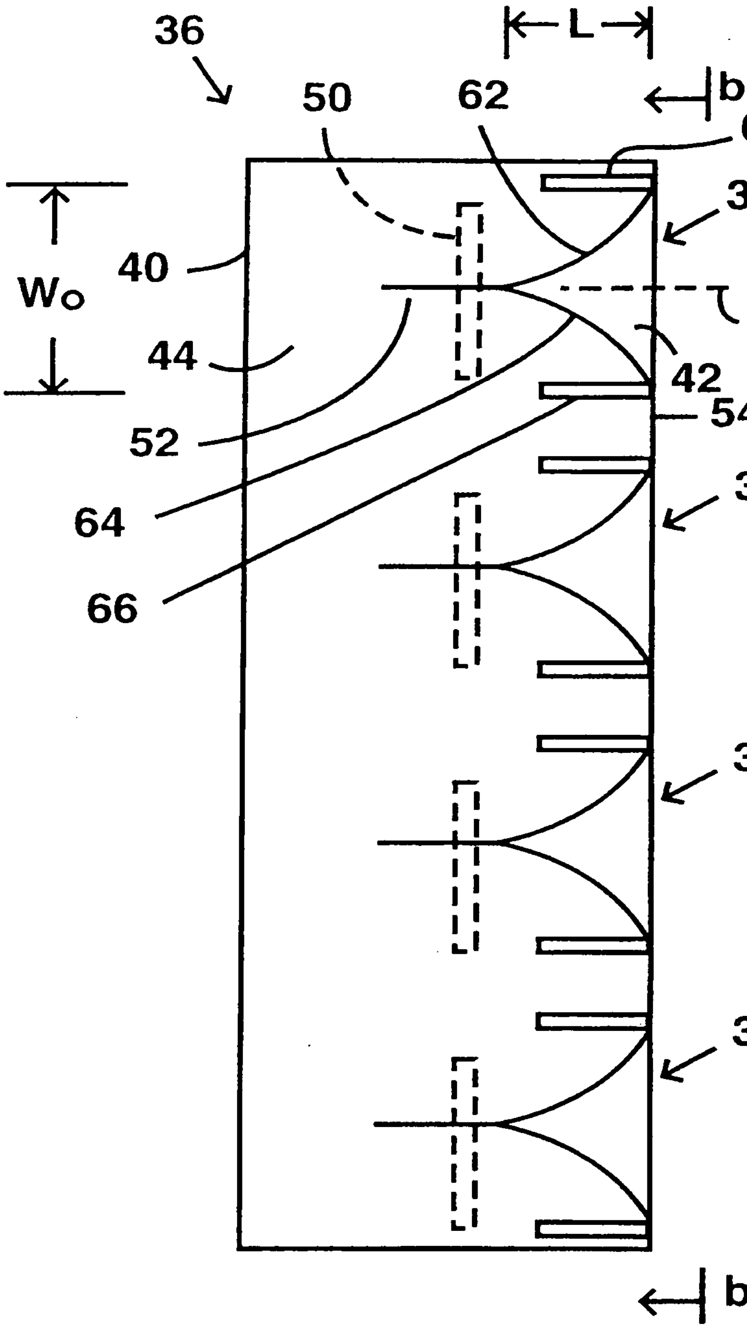

FIG. 4 (a)

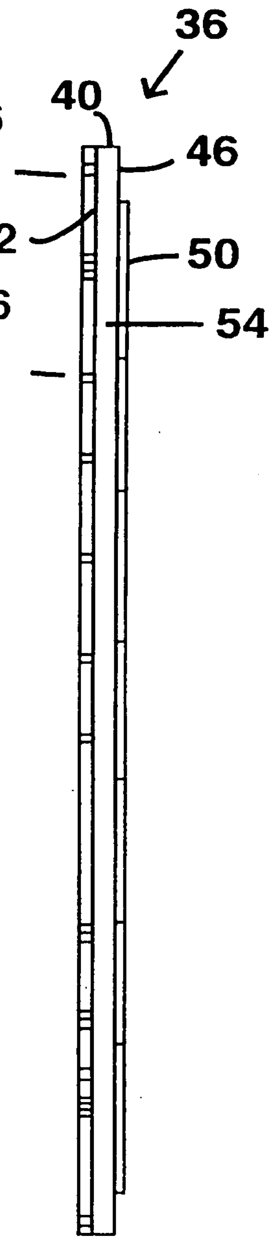

FIG. 4 (b)

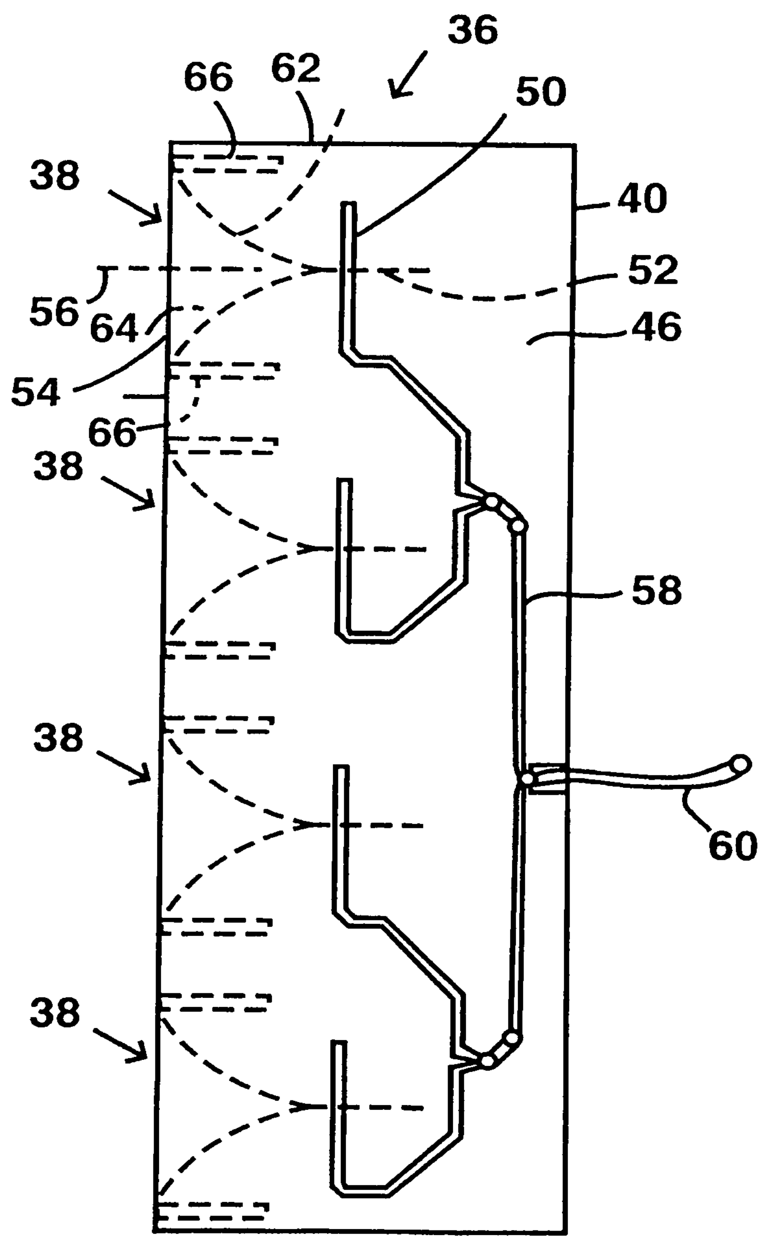

FIG. 4 (c)

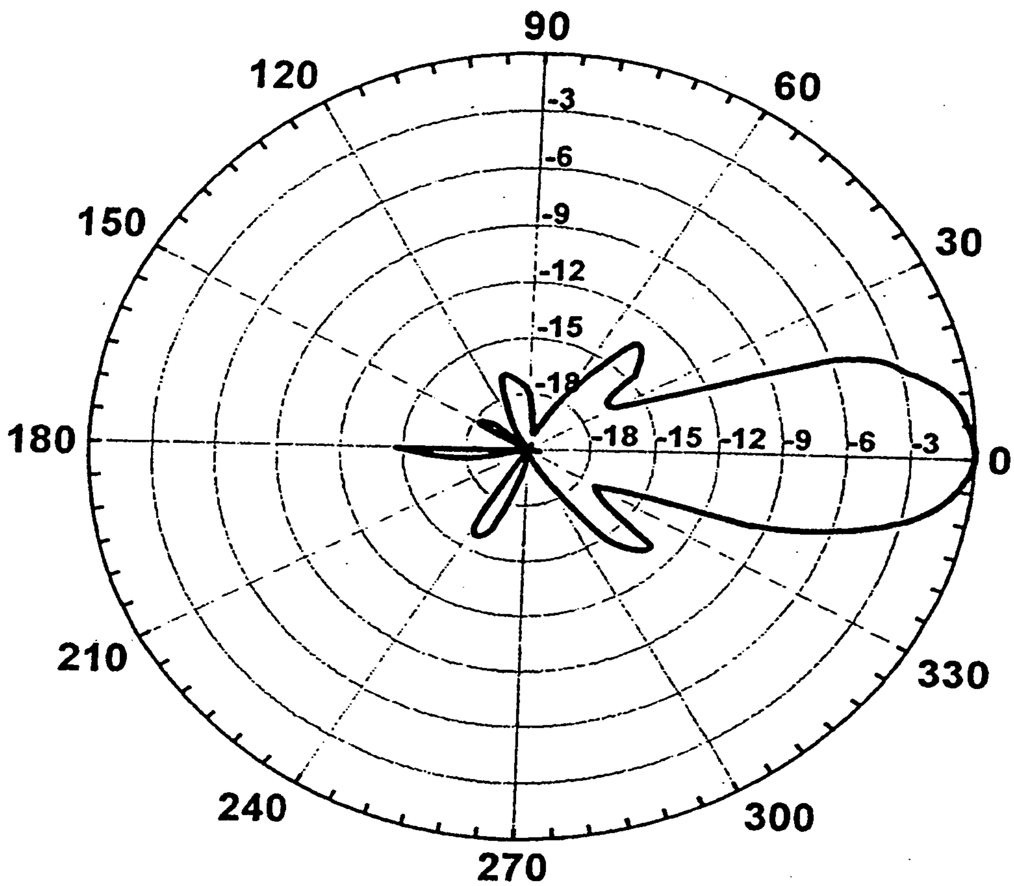

Fig. 5(a)

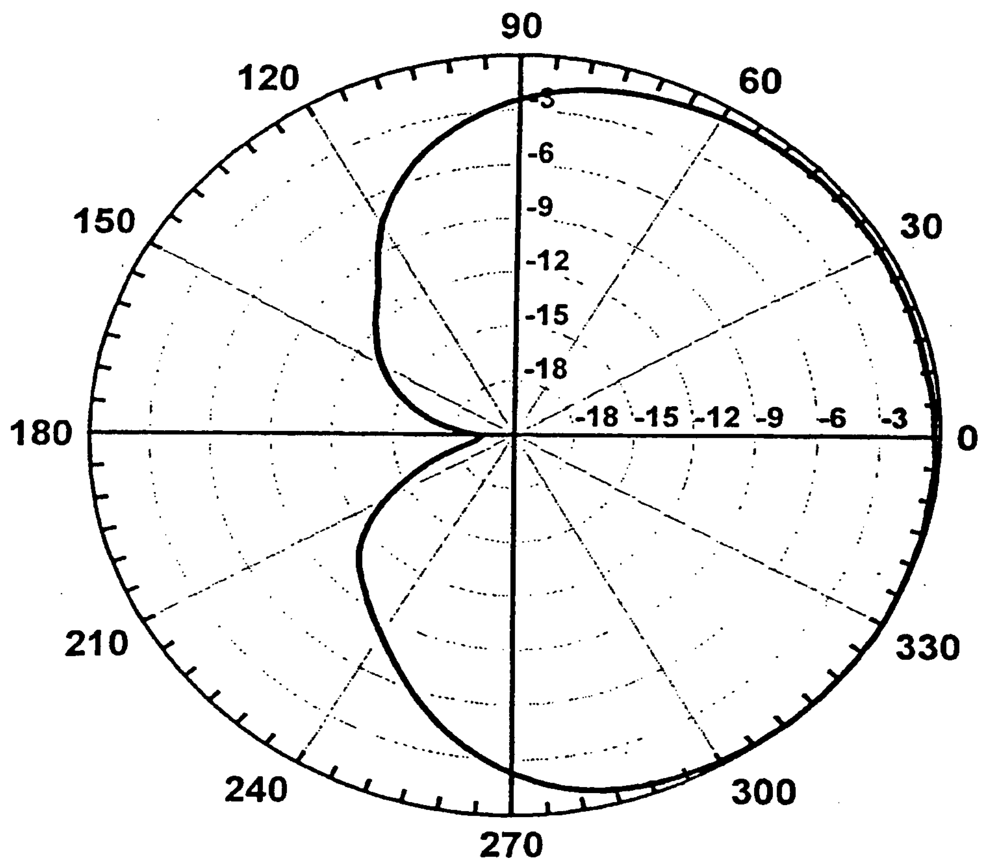

Fig. 5(b)

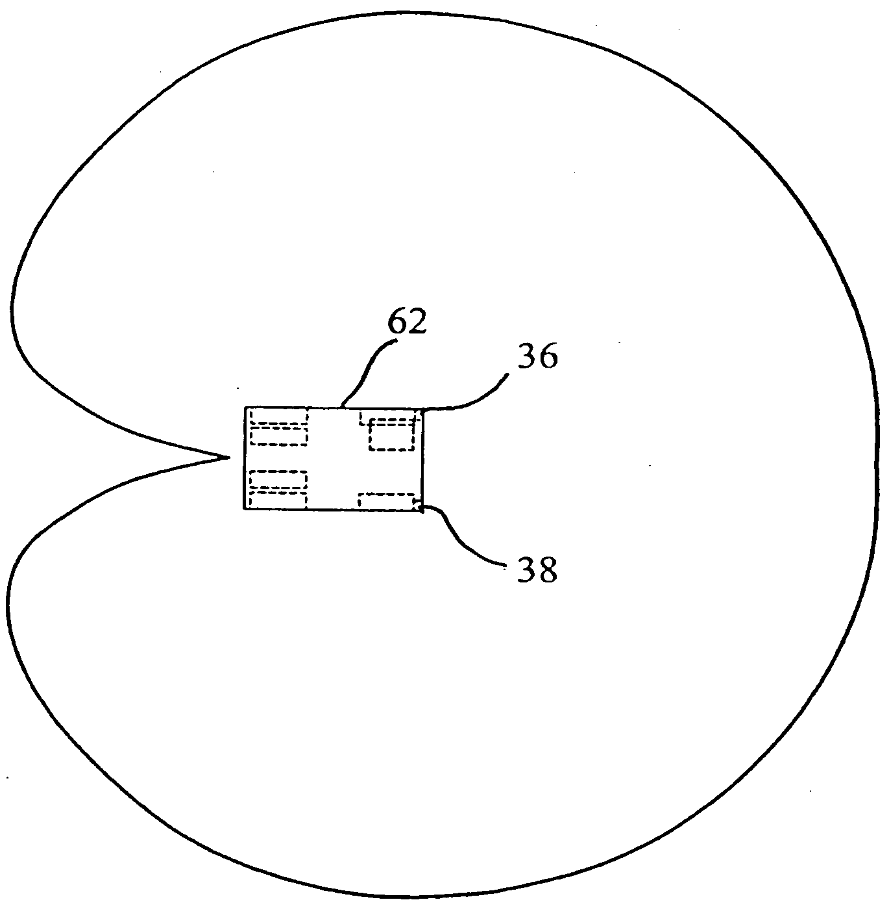

Fig. 6(b)

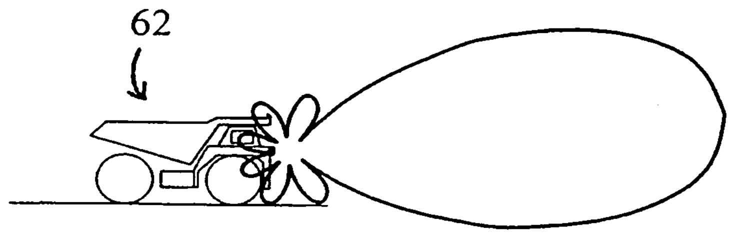

Fig. 6(a)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/35114

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H01Q 13/10, 1/38, 1/32
US CL : 343/767, 700MS, 770, 711
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 343/767, 700MS, 770, 771, 711, 712, 713

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

US, EPO, JPO, IBM DB
Search terms: tapered, slot, antenna. array,microstrip, stripline

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,043,785 A (MARINO) 28 March 2000, (28/03/00) Figs. 3, 4; Col. 3, line 8- Col. 4, line 32)	1-11
A	US 5,519,408 A (Schnetzer) 21 May 1996, (21/05/96) see entire patent	1-11
A	US 5,227,808 A (Davis) 13 July 1993, (13/07/93) see entire patent	1-11

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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